Cosmic Rays

II The origin of cosmic rays

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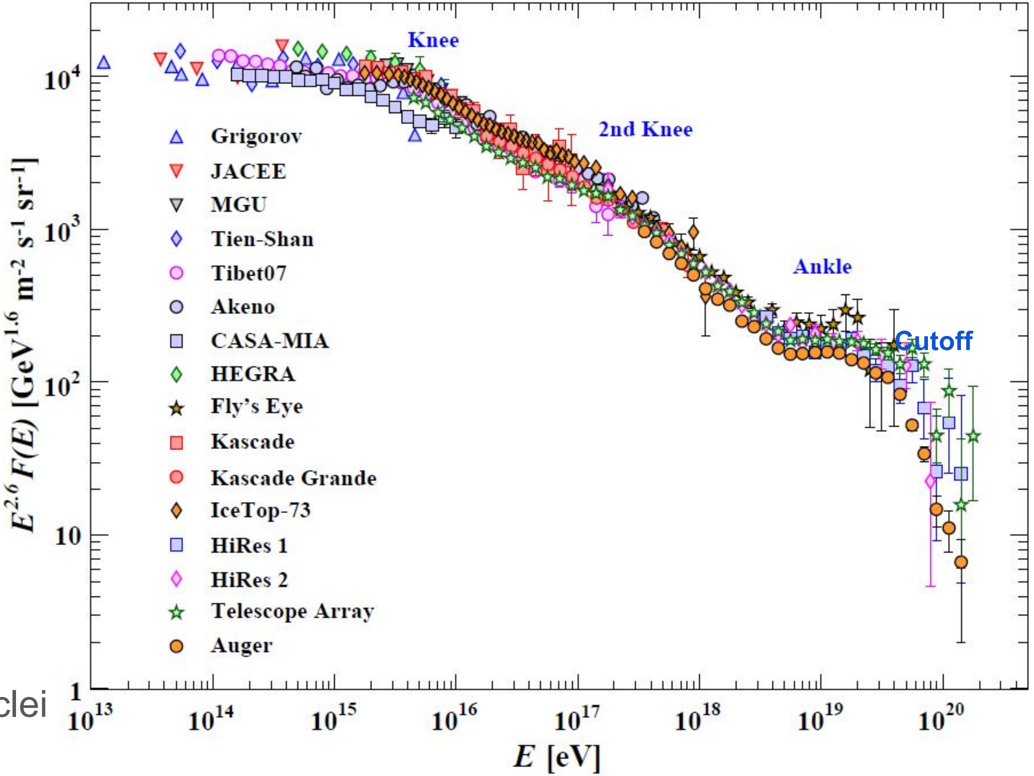
Where is the cosmic "LHC"?

- Since the early days, cosmic ray physicists are struggling to explain the mechanisms for accelerating particles up to such high energies
- Models accounting for production and propagation of cosmic rays should reproduce the non-trivial hints from cosmic phenomenology:
  - The power-law energy spectrum and its high-energy variations
  - The relative abundances of different nuclei

and the astrophysical observations



Cosmic Rays from the Sun?

- Stars in the "main sequence" like our Sun are nuclear reactors where hydrogen is burning through a well understood chain of reactions. For the Sun (and "light" stars) the main process is the ***pp* chain**

1a	$\mathrm{p} + \mathrm{p}$	$\longrightarrow {}^{2}\mathrm{H} + \mathrm{e}^{+} + \nu_e$
1b	$\mathrm{p} + \mathrm{e}^{-} + \mathrm{p}$	$\longrightarrow {}^{2}\mathrm{H} + \nu_e$
2	${}^{2}\mathrm{H} + \mathrm{p}$	$\longrightarrow {}^{3}\mathrm{He} + \gamma$
3a	${}^{3}\mathrm{He} + {}^{3}\mathrm{He}$	$\longrightarrow {}^{4}\mathrm{He} + 2\,\mathrm{p}$
3b	${}^{3}\mathrm{He} + {}^{4}\mathrm{He}$	$\longrightarrow {}^{7}\mathrm{Be} + \gamma$
3c	${}^{3}\mathrm{He} + \mathrm{p}$	$\longrightarrow {}^{4}\mathrm{He} + \mathrm{e}+ + \nu_e$
4a	${}^{7}\mathrm{Be} + \mathrm{p}$	$\longrightarrow {}^{7}\mathrm{Li} + \nu_e$
4b	${}^{7}\mathrm{Be} + \mathrm{p}$	$\longrightarrow {}^{8}\mathrm{B} + \gamma$
5a	${}^{7}\mathrm{Li} + \mathrm{p}$	$\longrightarrow 2 \times {}^{4}\mathrm{He}$
5b	${}^{8}\mathrm{B}$	$\longrightarrow {}^{8}\mathrm{B}^{*} + \mathrm{e}^{+} + \nu_e$
6b	${}^{8}\mathrm{B}^{*}$	$\longrightarrow 2 \times {}^{4}\mathrm{He}$

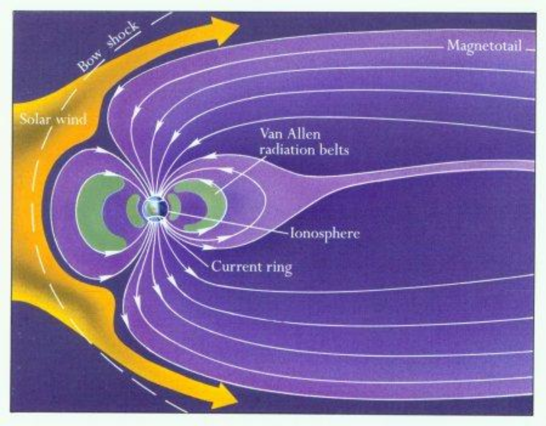
- The only escaping particles are neutrinos with E<20 MeV
- Clearly not the source of high energy cosmic rays

Cosmics from the Sun: the Solar Wind

- Temperature in the Sun's corona can reach 1 MK and particles with energies ~ 1 keV can escape Sun's gravity and produce the so-called **solar wind**. Clearly visible from the tails of comets

- Directly observed with inter-planetary probes (Voyager missions)

@1AU: Plasma (e,p,He ions) 9 particles/cm-3
flux speed ~350 km/s
thermal spectrum Tp ~ 4104 K
B field ~ 4 nT

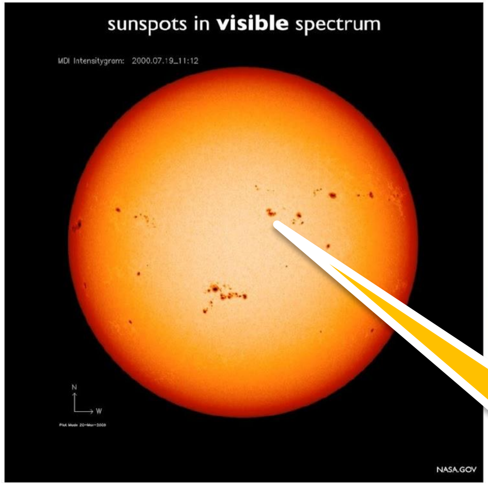


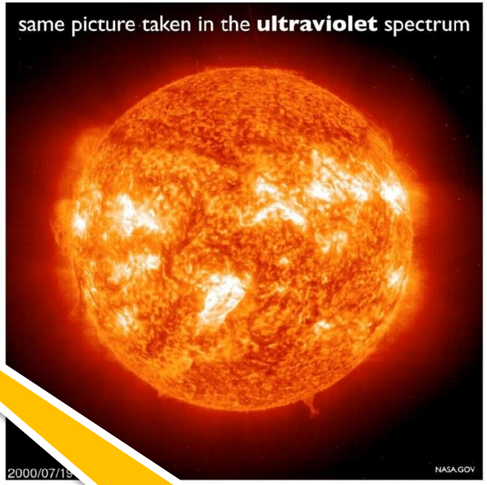
- Interacts with Earth's magnetic field. Varying solar activity (e.g. flares) can cause auroras (particles entering atmosphere at the poles)

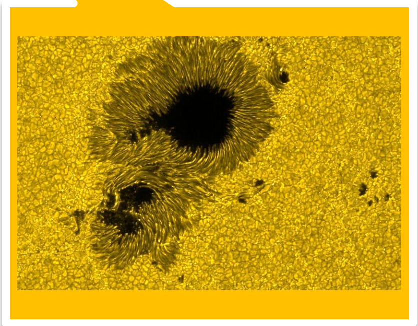
- Through its magnetic field, modifies CR spectra up to 10 GeV !

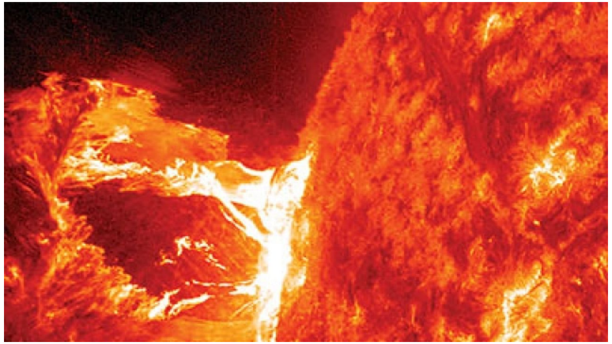
Cosmics from the Sun: Sunspots and Flares

- **Sunspots** are regions with strong magnetic activity
- Magnetic energy is sometime released suddenly into **Solar flares** (with or without coronal mass ejection)
- Particles can be accelerated up to 1 GeV energy
- Flares toward the Earth can cause magnetic storms and bright auroras



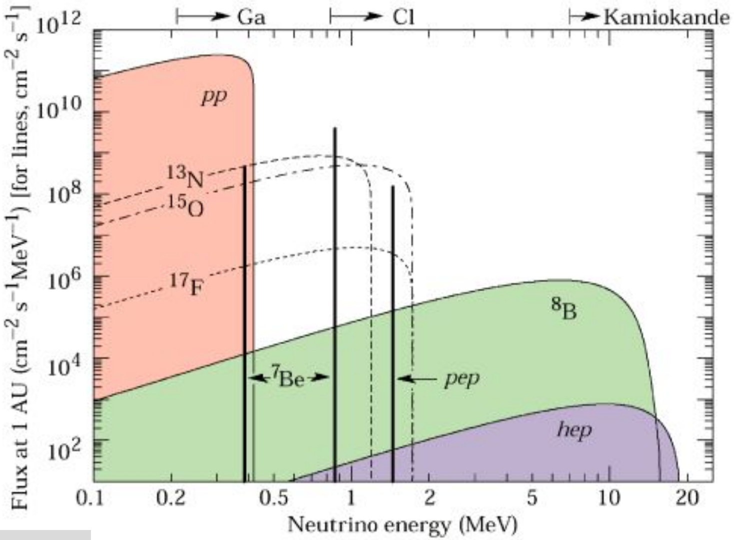


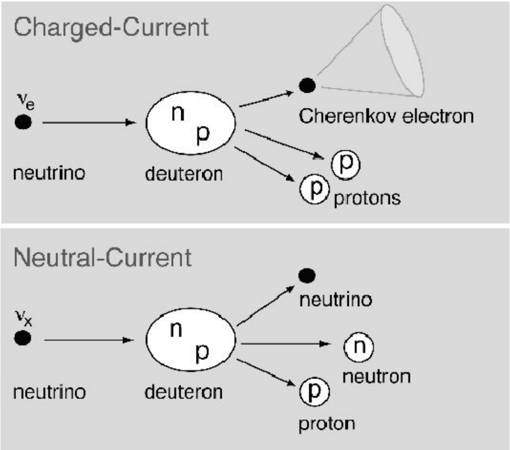


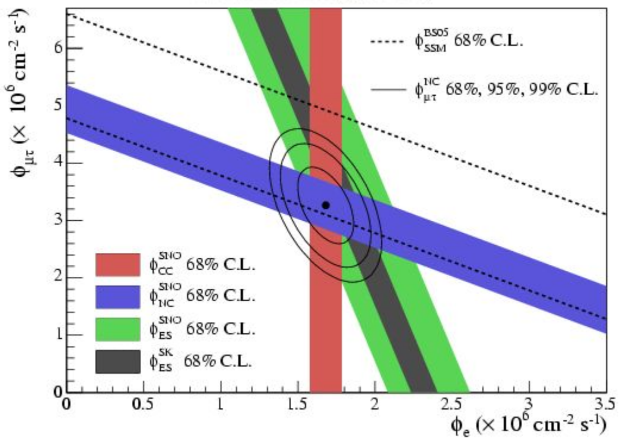


Cosmics from the Sun: Neutrinos!

- The solar neutrino flux can be predicted from the Standard Solar Model
- First detection performed by the Chlorine experiment in the 1960s, rate of charged-current neutrino events found to be less than half of the expected one…
- Puzzle solved in 2002 by the detection of neutral current events (sensitive to all flavours) by the SNO experiment: the total neutrino flux was found to be compatible with predictions, deficit of ν_e charged-current events explained through **neutrino flavour oscillations**

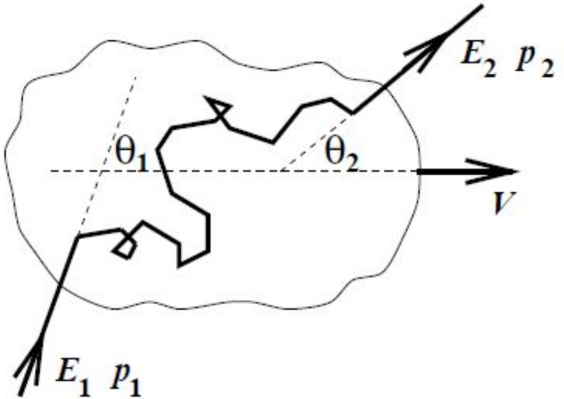






Looking for a 10^{20} eV accelerator

First idea: the **Fermi acceleration** (1949)



- Stochastic effect of interactions of charged particles with moving large clouds of ionized gas with varying magnetic fields
- In cloud frame energy is conserved and motion is random:

$$E'_2 = E'_1 \qquad \langle \cos\theta'_2 \rangle = 0$$

- In "lab" frame

$\gamma = 1/\sqrt{1-\beta^2}$ $\quad$ $\beta = V/c$

$$E'_1 = \gamma E_1 (1 - \beta\cos\theta_1)$$

$$E_2 = \gamma E'_2 (1 + \beta\cos\theta'_2)$$

$$\langle \cos\theta_1 \rangle = \int \cos\theta_1 \frac{dP}{d\Omega_1} d\Omega_1 \Big/ \int \frac{dP}{d\Omega_1} d\Omega_1 = -\frac{\beta}{3}$$

$$\Rightarrow \quad \frac{\langle \Delta E \rangle}{E} = \frac{1+\beta^2/3}{1-\beta^2} - 1 \simeq \frac{4}{3}\beta^2$$

- Net energy increase (on average) at each random crossing
- But energy conversion is inefficient: $\beta \sim 10^{-4}$ in actual nebulae

Spectrum from Fermi acceleration

- Is particle makes n crossings with $\langle \Delta E/E \rangle = \epsilon$, average energy increase will be

$$E = E_0 \cdot (1+\epsilon)^n \quad \Rightarrow \quad n = \frac{\ln(E/E_0)}{\ln(1+\epsilon)}$$

- If P_{esc} is the probability to escape the acceleration region, the number of particles with energy larger than E is

$$N(\geq E) = N_0 \cdot (1 - P_{esc})^n \quad \Rightarrow \quad n = \frac{\ln(N/N_0)}{\ln(1-P_{esc})}$$

$$\Rightarrow \quad \frac{N}{N_0} = \left(\frac{E}{E_0}\right)^{-\gamma+1}$$

$$\frac{dN}{dE} \propto E^{-\gamma}$$

$$\gamma = 1 - \frac{\ln(1-P_{esc})}{\ln(1+\epsilon)} \sim 1 + \frac{P_{esc}}{\epsilon}$$

$\Rightarrow$ The energy spectrum follows a power-law with spectral index γ

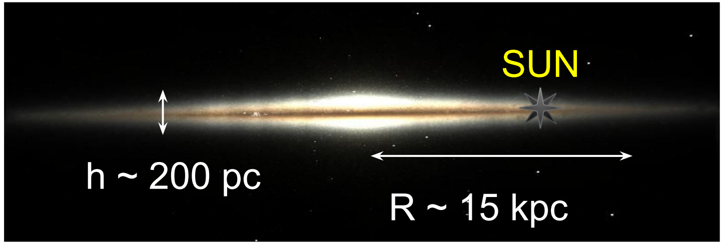
Power of cosmic accelerators

- Energy density of cosmic rays

$$\rho_{CR} = \int dE\ E_k n(E) = 4\pi \int dE\ \frac{E_k}{v} I(E) \sim 1\,\mathrm{eV/cm^3}$$

- Volume of the Galactic disk

$$V_D = \pi R^2 h \sim 4 \times 10^{66}\ \mathrm{cm}^3$$



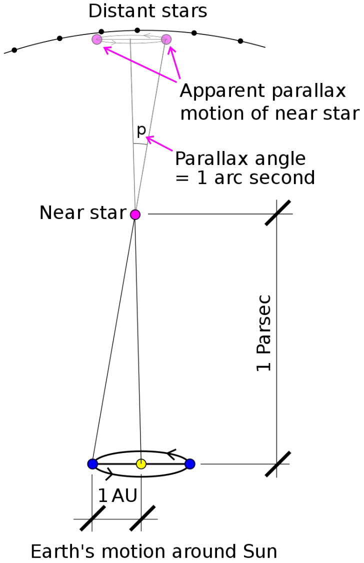
$$1\ \mathrm{AU} = 1.50 \cdot 10^{11}\ \mathrm{m} = 1.58 \cdot 10^{-5}\ \mathrm{ly}$$
$$1\ \mathrm{pc} = 1\ \mathrm{AU}/\tan(1") = 3.09 \cdot 10^{16}\ \mathrm{m} = 3.26\ \mathrm{ly}$$

- Typical CR lifetime $\tau^{esc}=10^7$ years (see later)

⇨ power must be

$$V_D \rho_{CR}/\tau^{esc} \sim 2 \cdot 10^{33}\ \mathrm{W}$$

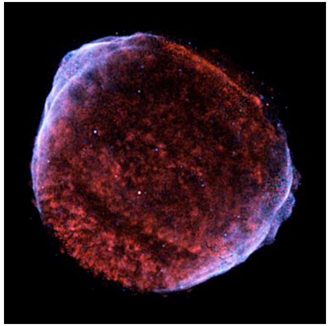
(for comparison: power of the Sun ~ 4 10^{26} W)



- Few astrophysical phenomena can release such energies as high-energy particles, **SuperNova (SN) explosion** is the main suspect

Historical observations of SN explosions

❑ **SN185** first (clearly) recorded SN event by Chinese astronomers



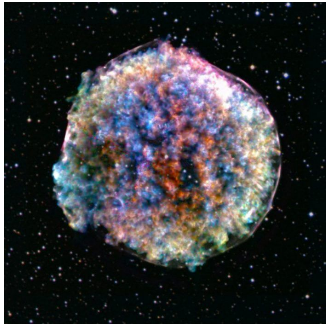
SN1006 today: remnant in the Lupus, discovered in 1965

❑ **SN1006** probably the brightest SN events seen in human history, documented among others by Ali Ibn Ridwan

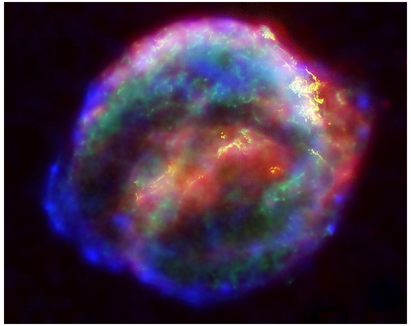
“was a large circular body, 2½ to 3 times as large as Venus. The sky was shining because of its light. The intensity of its light was a little more than a quarter that of Moon light”

was visible for 3 months, only 2.2 kpc from us!

❑ **SN1572** observed by Tycho Brae



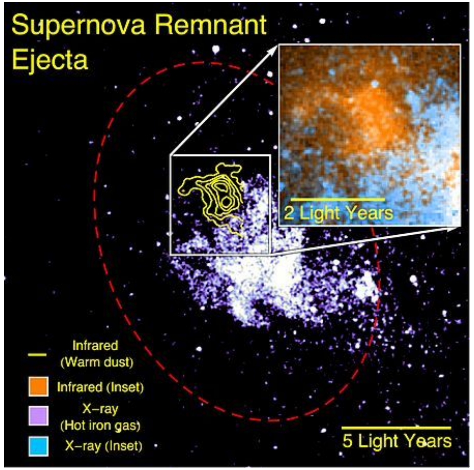
❑ **SN1604** observed by Kepler, latest event visible by naked eye in the Milky Way

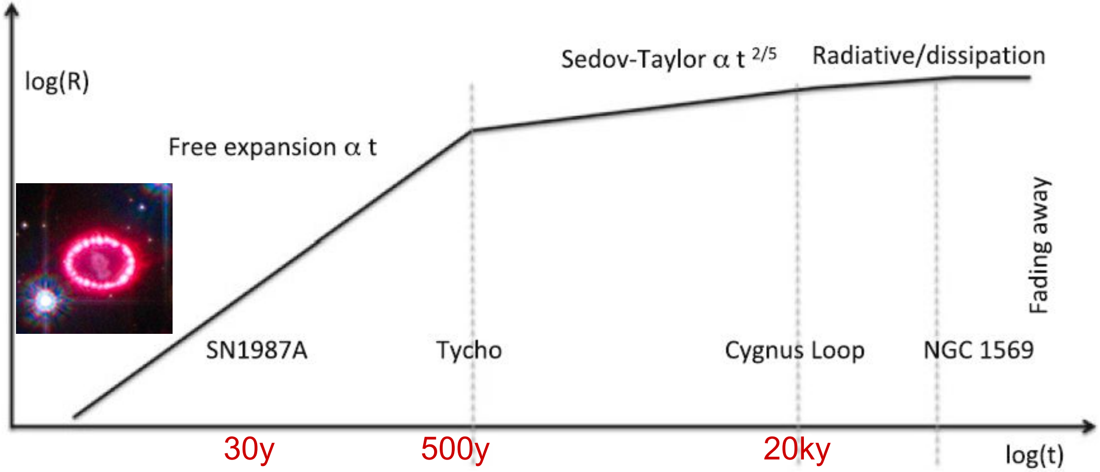


❑ **SN1987a**   the brightest SN observed with modern instruments

SN facts

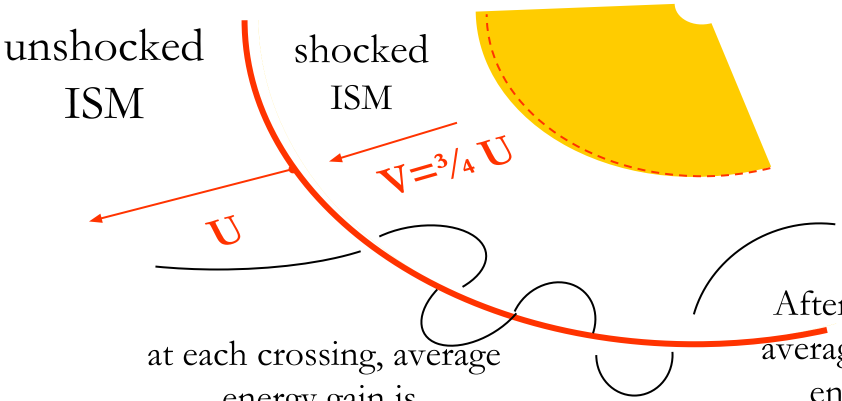
- ❑ Despite the name (Nova=new), SN explosion marks the end of life of a star, when the nuclear fuel is exhausted and the gravitational potential energy is released
- ❑ Within our galaxy, we expect one event every ~30 year
- ❑ But we now observe hundreds events/year from other galaxies
- ❑ The explosion produces a **SuperNova Remnant (SNR)**:
  ”bubble” expanding for ~ 50 ky reaching sizes of ~ 50 ly
- ❑ In the initial expansion, a shock wave propagates at supersonic speed (up to 10^4 km/s), sweeping the interstellar medium





Shock waves in SN remnants

- Fermi's stochastic acceleration occurs at the front of the shock wave: **diffusive shock acceleration**
- When crossing the wave front, particles scatter with a high-density magnetized gas and can bounce back multiple times
- Kinetic theory of gas for supersonic shocks in a monoatomic gas: relative velocity between shocked and unshocked gas is $V = \frac{3}{4} u_1$ where u_1 is the shock wave speed ~ 10^4 Km/s
- More efficient acceleration wrt to randomly distributed clouds, due to the coherence of the moving wave



at each crossing, average energy gain is

$$\varepsilon = 4/3\ V/c = 4/3$$

After n cycles average particle energy is

$$E = E_0 \cdot (1+\varepsilon)^n$$

1st order Fermi acceleration: gain ∝

Escape probability

$$P_{esc} = 4/3 \quad \sim \quad \varepsilon$$

Spectral Index at source

$$\gamma \sim 1 + P_{esc}/\varepsilon \sim 2$$

Propagation also depends on energy

$$(dN/dE)_{earth} \propto (dN/dE)_{source}\ E^{-\delta}$$

with $\delta = 0.6$ (see later)

→ $\gamma \sim 2.6$ at Earth detection as seen experimentally!!

Power and Maximum Energy

- Typical SNR shock energy release: 10^{44} J
- Power for 1 event every 30 y is thus $P_{SNR} = 10^{44} \mathrm{J}/(30 \cdot \pi \cdot 10^{7}\ \mathrm{s}) \sim 10^{35}\ \mathrm{W}$

⇨ Enough to power CRs with 2% of acceleration efficiency!

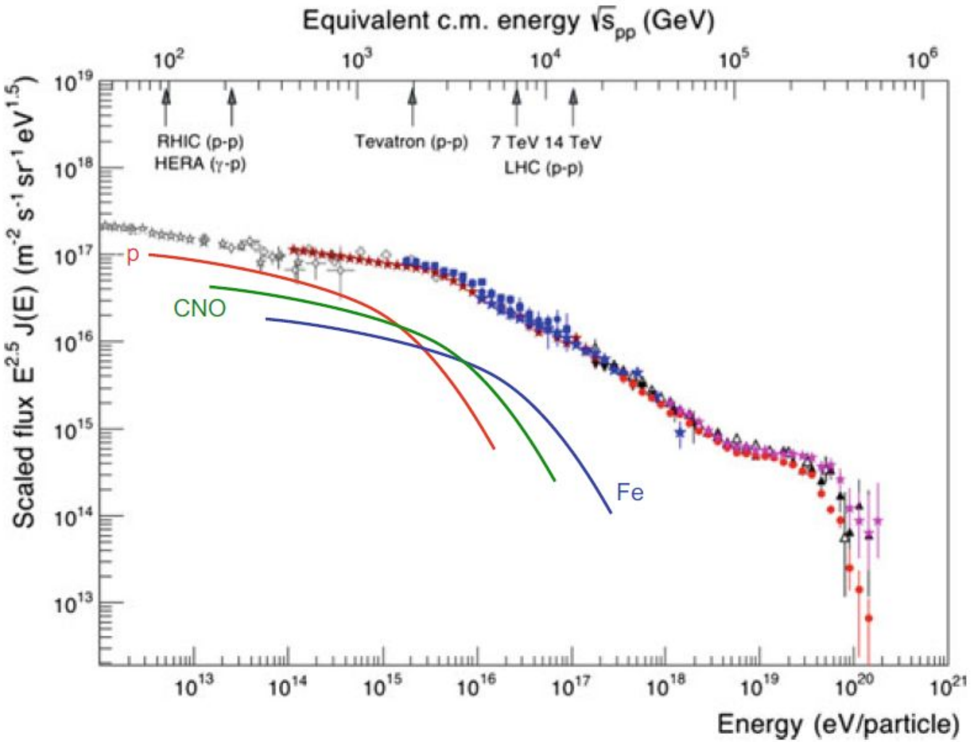
- The maximum particle energy is limited by the SNR size *L* (few ly) nd magnetic field *B* *(few* μG*)*: particles can't be contained if *L* is smaller that the gyroradius

$$r_L \equiv \frac{p_\perp}{ZeB}$$

- Estimated maximum for SNR is

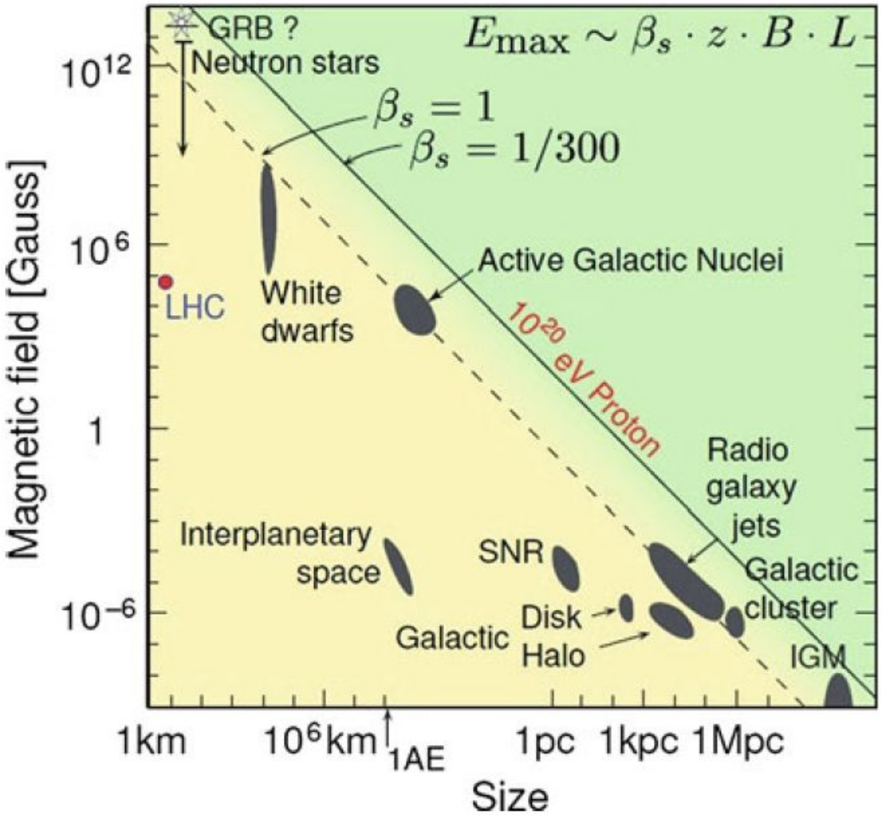
$$E_{max} \sim 300 \cdot Z \cdot \mathrm{TeV}$$

plausible explanation for the knee!



Other candidate acceleration sites

- In general, size and magnetic field of possible acceleration sites determines the maximum energy: Hillas plot
- s is the acceleration efficiency
- Active Galactic Nuclei (black holes with spinning accretion disks at the galaxy centers) are among the possible sites capable to explain 10^{20} eV



Propagation of cosmic rays

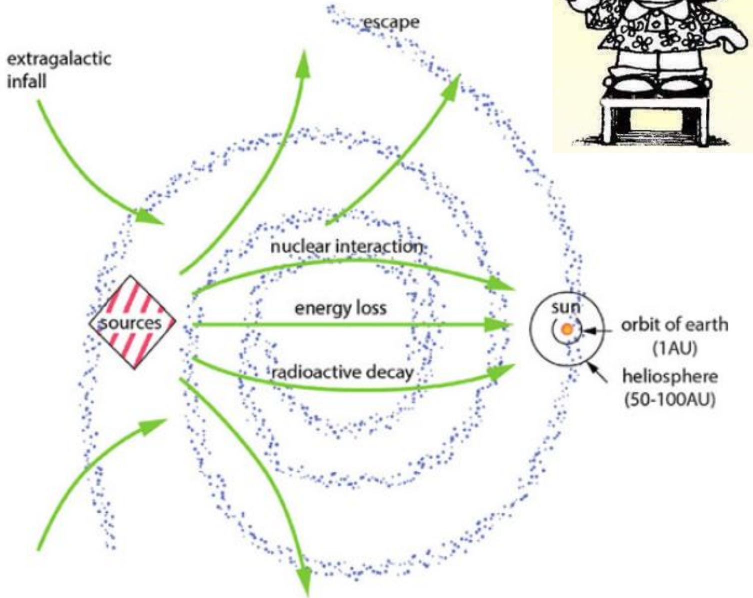
- Containment of cosmic rays within the Galaxy is due to magnetic fields

gyroradius r_L at relativistic speed :

$$r_L/(1\,\mathrm{m}) \sim 3.3/Z \cdot E/(1\,\mathrm{GeV}) \cdot (1\,\mathrm{T})/B$$

$$r_L/(1\,\mathrm{kpc}) \sim 1/Z \cdot E/(1\,\mathrm{EeV}) \cdot (1\,\mu\mathrm{G})/B$$

- Before reaching the Earth, cosmic particles can
  - escape the Galaxy
  - interact with the Inter Stellar Medium:
    - B field (~ 1 μG): diffusion
    - Gas: ~1 nucleon/cm^3 (90% H, 10% He)
      - nuclei produce lighter species by spallation
      - energy loss by radiation
  - decay (if unstable)



Transport equations

- Set of coupled differential equation for each species i

$$\frac{\partial n_i}{\partial t} = q_i + \nabla \cdot \left(\hat{\boldsymbol{k}} \nabla n_i - \boldsymbol{u} n_i\right) - p_i n_i + \sum_{k>i} p_{k \to i} n_k - \frac{\partial}{\partial E}\left(b_i n_i\right)$$

Sources

Diffusion and Convection

Loss and production through interactions and decay

Energy variations: ionization losses, radiation, reacceleration

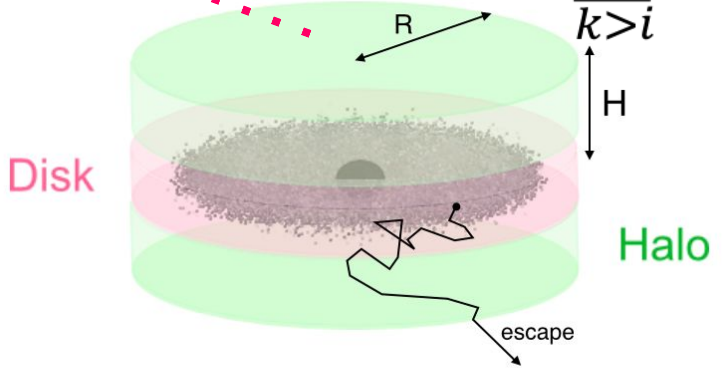
$$b_i = b_i(E, t) = \frac{dE}{dt}$$

$n_i(E,r,t)$ is the CR density

- Can be solved numerically through simulation codes (e.g. GALPROP), taking into account realistic distribution of sources, magnetic field maps, etc.
- Diffusion parameters and amount of crossed interstellar gas (related to time of survival in the galaxy) are obtained from fits to experimental data

The "Leaky box" model

$$\frac{\partial n_i}{\partial t} = q_i + \nabla \cdot (\hat{\boldsymbol{k}} \nabla n_i - \boldsymbol{u} n_i) - p_i n_i + \sum_{k>i} p_{k\to i} n_k - \frac{\partial}{\partial E}(b_i n_i) - \frac{n_i}{\tau_{esc}}$$



Only for nuclei: neglect ionization losses

- Main features of the propagation reproduced by a simple model assuming stationary and uniform density where sources are compensated by losses ("leaky box" model). The only free parameter is the escape time $\tau_{esc}(E,Z)$
- For each species, losses depend on the interaction length $\lambda_P = m_g/\sigma_i$ and the escape length $\lambda_{esc} = m_g\, n_g\, v\, \tau_{esc}$ which is the average crossed matter (m_g n_g mass and density of inter-stellar gas)

Measuring escape time with secondaries

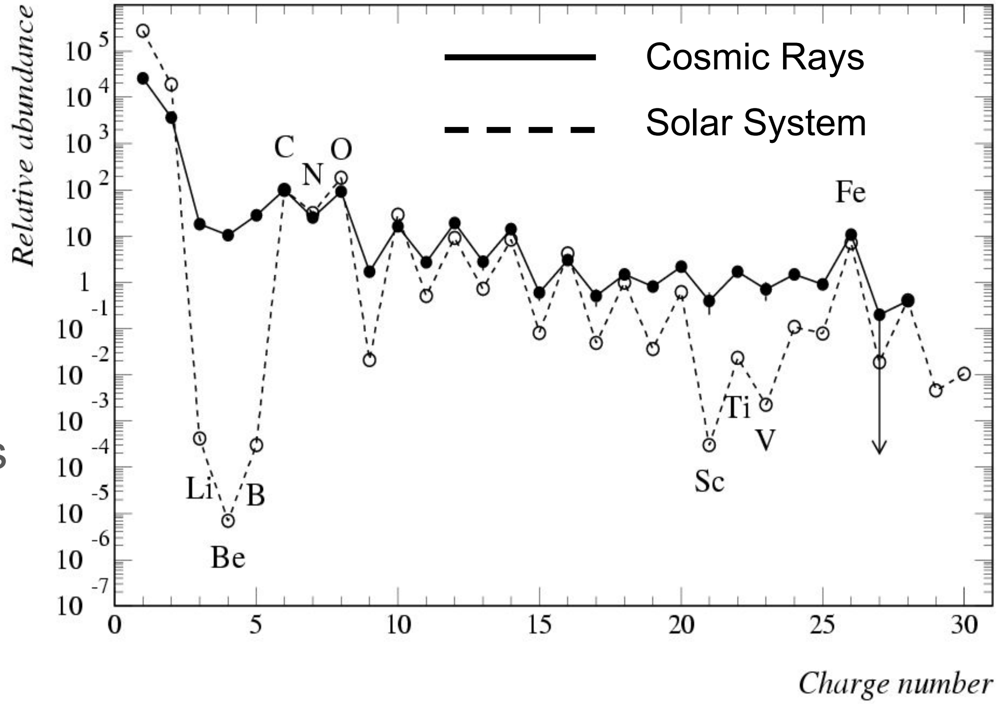
- Solving the diffusion equation one expects τ_{esc} of order 10^7 years and $\tau_{esc} \propto E^{-\delta}/Z$

- Unstable secondary nuclei with lifetime ~ τ_{esc} can be used as "cosmic ray clocks", e.g.

$$^{10}\mathrm{Be}\ (\tau \sim 2.2\ \mathrm{Myr}),\ ^{26}\mathrm{Al}\ (\tau \sim 1.2\ \mathrm{Myr})$$

by measuring their relative abundances wrt the stable isotopes

- Secondary/primary for stable nuclei, e.g. B/C can be used to determine λ_{esc}

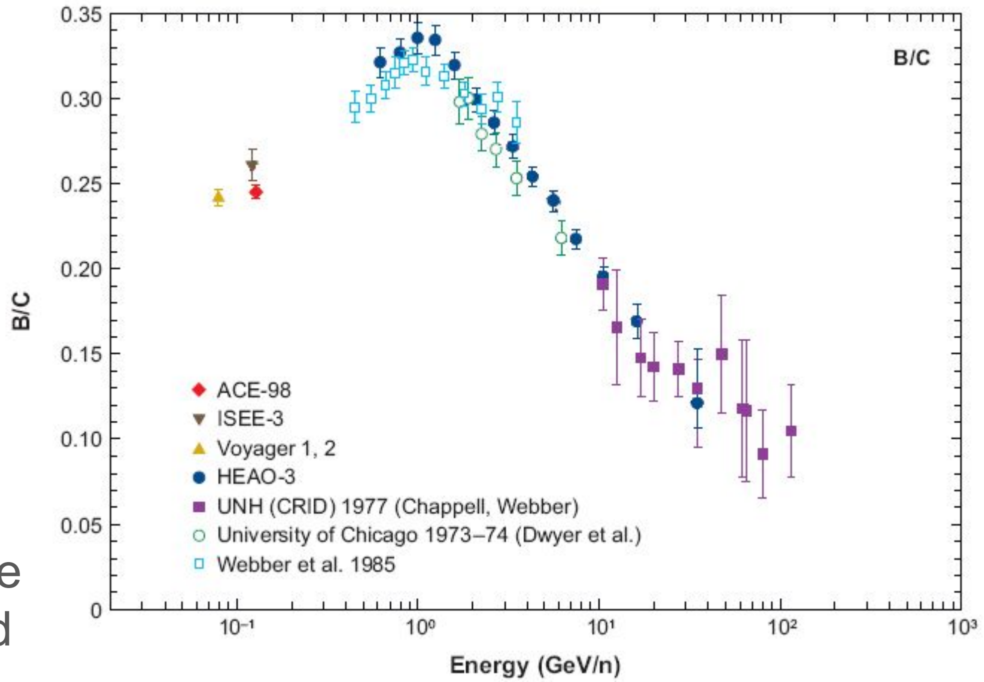


Secondary/primary ratio

- Secondary/primary ratios are key quantities to be determined experimentally
- In the leaky box model, assuming all secondaries (S) come from the same primary (P) species

$$\frac{n_S}{n_P} = \frac{\lambda_{esc}/\lambda_{P\to S}}{(1+\lambda_{esc}/\lambda_S)}$$

- Knowledge of the cross-section for the P->S spallation procession is required
- Result is δ ~ 0.6



- High-energy protons have $\lambda_P >> \lambda_{esc}$, so their spectra is simply

$$N_P(E) = Q_P(E)\tau_{esc}(E) \propto E^{-\gamma}E^{-\delta} \sim E^{-2.6}$$

Extragalactic CR: the GZK cutoff

- The highest CR reaching the Earth are expected to have escaped from galaxies containing powerful CR sources, propagating in the inter-galactic medium

	B-field	Gas density
Galactic space	~ 1 μG	~ 1 nucleon/cm^3
Inter-galactic space	10^{-9} - 10^{-15} G	~ 1-10 nucleon/m^3

- Energy is limited by interactions with **Cosmic Microwave Background** as realized in 1966 by Greisen, Zatsepin and Kuzmin (GZK)
- Threshold for the process $p\,\gamma_{CMB} \rightarrow \Delta^+ \rightarrow p\,\pi^0\ (n\,\pi^+)$

  is **$6\ 10^{19}$ eV** and the corresponding mean free path is ~ 10 Mpc

- A cutoff in the spectrum is thus expected, the detailed shape depends on the CR composition and the distance from the sources

The experimental challenge

- Models of CR acceleration in SNR and propagation provide a picture consistent with the experimental observations, but not yet fully proved
- Many large experimental efforts ongoing to turn cosmic ray physics into precision science:
  - experiments in **Space** are accessing spectrum and composition of charged particles up to the **TeV** scale;
  - **large detector arrays** studying atmospheric showers at the highest energies: composition above the knee is particularly relevant to test models and is still poorly known;
  - direct observation of possible acceleration sites is becoming possible though neutral messenger: **gamma and neutrino** observatory;
  - cross-section measurements at **accelerators** complement these studies
- More precise understanding of **astrophysical** mechanisms improve sensitivity to unexpected contributions, e.g. dark matter annihilation

⇒ possible new inputs to **particle physics**